*M*otor with *A*dvanced *C*oncepts for *H*igh power density and *IN*tegrated cooling for *E*fficiency (MACHINE)

DE-EE0008867

DOE/VTO Annual Merit Review Presentation

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Raytheon Technologies Research Center

June 21-25, 2022

Project ID: ELT253

RTRC Team: Bob Dold, Stephen Du, Kenji Homma, Kim Saviers, Sunilkumar Soni, Jagadeesh Tangudu (PI), Joe Turney

John Deere Team: Robert Salamon, Brij Singh (Co-PI)

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Project Overview

Timeline

Project Start Date: Oct 2019 (Jan 2020)
Project End Date: Jun 2022
Percent Complete: 85%
Delays associated with supply chain, shipping and other delays

Budget

Total Project Budget
DOE Share: $750k
Cost Share: $187.5k

Funding for 2020: $599.6k
Funding for 2021: $337.9k
Funding for 2022: No Cost Extension

Program Barriers

Project goals include the following

- High power density (>8X)
- Lower motor cost (< $6/kW)
- Improve life (>2X)

These project goals are extremely challenging…

- Increased power density require reduction in volume
- One option to achieve is by increasing the speed (>20 kRPM)
- High speed operation would present mechanical challenges along with limited pole count
- High frequency also brings in higher loss density and challenging thermal management

Partners

- Raytheon Technologies Research Center
  (formerly known as United Technologies Research Center)
- John Deere

Multi-Disciplinary Team

Project Management: Raytheon Technologies

Project PI: Dr. Jagadeesh Tangudu

Motor Design Raytheon Technologies

Dr. Zhentao (Stephen) Du

Dr. Jagadeesh Tangudu

Bob Dold

Thermal Management Raytheon Technologies

Dr. Kimberly Saviers

Dr. Joseph Turney

Dr. Kenji Homma

Dr. Sunil Soni

Application Specifications John Deere

Co-PI: Dr. Brij Singh

- Seedling project
- Evaluate proposed technology during BP-1 and down-select technologies suitable for meeting target metrics
- Path for risk reduction using sub-component demonstrations during BP-2
- Multi-disciplinary team to explore the optimal solutions

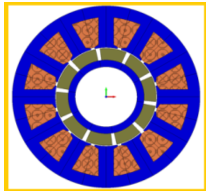
Challenges

- Increase in 8X volumetric power density is a challenging target to meet
- Achieving this would require increase in speed, but this posed two critical challenges
  - Trade between concentrated (limited slot-pole combination) vs. distributed winding (larger end winding)
  - Use of non-heavy rare earth magnets reduces the energy product and operating temperatures
  - Increase in fundamental frequency, i.e., increase in core losses as well as increase in AC winding losses in copper
  - Mechanical challenges such as rotor dynamics, centrifugal loads, larger air gap’s (lower power density), bearing life, mechanical losses etc.
  - Thermal management of the motor is also critical for improved life and efficiency
- Use of reduced loss steel (for mitigating high frequencies) and Litz’s wire (for AC winding losses) would increase material and manufacturing cost
- Impact of technologies required to meet the power density metrics while minimizing the cost and life is critical

Project Objectives (Year 2020 / 22)

- Explore machine trade space
- Identify optimal operating speed (>20 kRPM)
- Use of non-heavy rare earth magnets
- Identify suitable lamination steel for reduced losses
- Evaluate achievable slot fill factor with segmented stator sections
- Optimal use of Electromagnetic and thermal management solutions to meet these stringent targets

Motor



Drive

Motor Target Metrics		
Specifications	Units	Values
Power Density (greater than)	kW/L	50
Cost (less than)	$/kW	6
Life (greater than)	X	2
Derived Metrics		
Peak Power	kW	125
Min Speed (greater than)	RPM	20000
DC Bus Voltage	V	1050
Volume (Less than)	l	2.5
Unit Material Cost (Less than)	$	750
Based Speed	RPM	20000
Peak Torque @ Base Speed	Nm	59.68

John Deere Drive [1]		
Specifications	Units	Values
Power	kW	200
Power Density	kW/L	40
Drive DC Bus Voltage	V	1050
RMS fundamental line-line voltage	V l-l RMS	690
Max Fundamental Frequency	kHz	2
Drive Switching Frequency	kHz	20
Number of Phases (>)	[-]	3

Source: 1. https://www.deere.com/en/electronic-solutions/news-room/news-articles/2nd-generation-sic-inverter/

Project Relevance

ETDS Targets			
Year	2020	2025	Change
Cost ($/kW)	8	6	25% cost reduction
Power Density (kW/L)	4.0	33	88% volume reduction

- Historically, VTO emphasized HEV applications, with target power levels at 55 kW [1]
- Vehicle mass has been increasing since then (>100kW) to meet consumer vehicle performance [1]
- Entire Electric Traction Drive Systems (ETDS) target metrics for 2025 <$6/kW & > 33kW/L [1]

Electric Motor Targets			
Year	2020	2025	Change
Cost ($/kW)	4.7	3.3	30% cost reduction
Power Density (kW/L)[1]	5.7	50	89% volume reduction

- Breaking down the target metrics to motor and drive would results in motor power density metrics > 50 kW/L with 89% reduction in volume [1]
- 100+ kW electric machine with its rotor, rotor shaft, stator with ending externs, housing and cooling but not reduction gearing [1]

1. Source: "USDRIVE Electrical and Electronics Technical Team Roadmap" October 2017

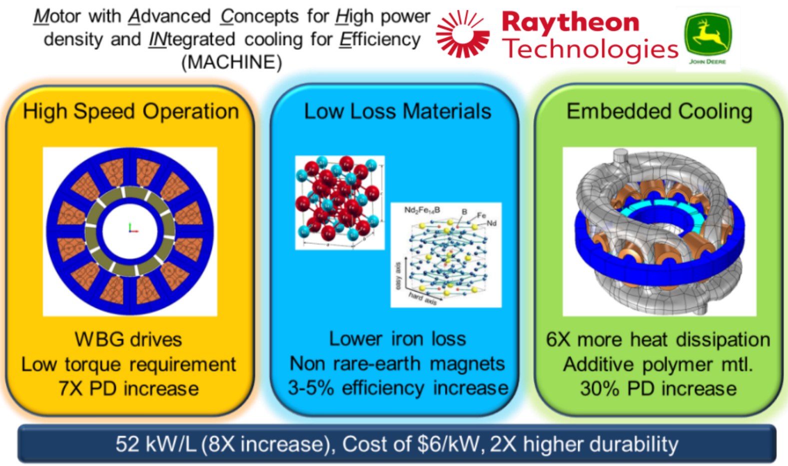
Uniqueness and Impact

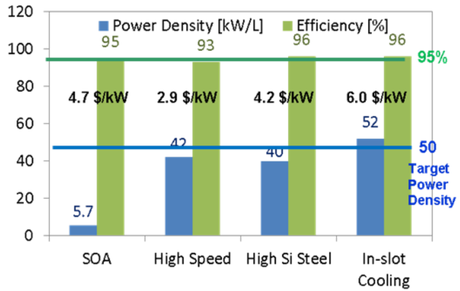
In-order to meet the target metrics proposed MACHINE concept uses a Motor Drive architecture

a) Wide Band Gap (WBG) drive
b) Segmented stator fractional slot concentrated windings (FSCW)
c) Surface mounted permanent magnets
d) Operating at speed (>20,000 rpm)
e) Materials
   - non-heavy rare earth
   - low loss electric steel for reduced core losses
f) In-slot ultra-low-volume embedded cooling channels

These technologies in combination would potentially lead to

1. volumetric power density of >50 kW/L
2. cost of $6/kW, and
3. 2X improvement in motor life





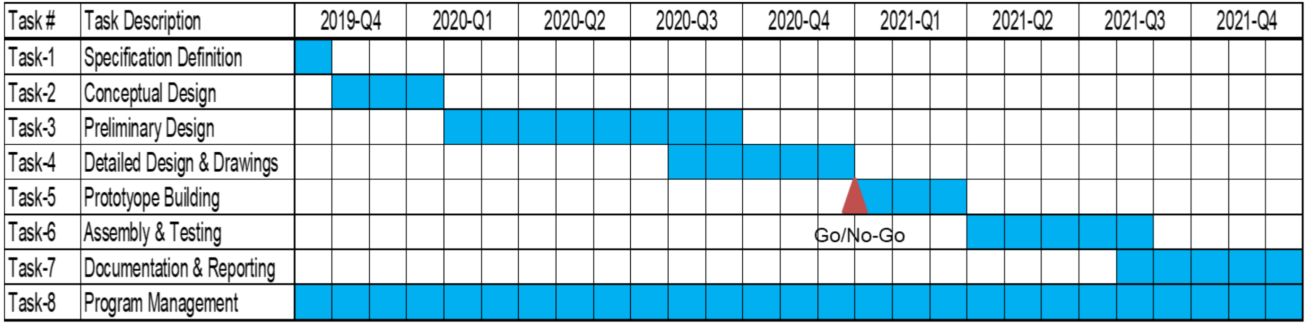
Project Approach

Proposed Approach for this project includes the following

- Electromagnetic design space evaluation: Identify an appropriate motor topology with in the suitable maximum fundamental frequency, winding architecture, materials, and key dimensions while applying assumptions, such as,
    - Segmented stator for higher slot fill factor
    - Slot-pole selection for maximum fundamental frequency to 2000 kHz
    - Low core losses by using high Silicon steel at high frequencies
    - Move loss density from core to copper losses
- Thermal management: Co-design methodology implemented to assess down-select EM configurations to evaluate the power density & cost
- Sectional stator prototype during BP-2 to reduce key in-slot cooling risks

Project Timeline & Milestones

Project Timeline (Original)



- Delays in contract negotiations along with personal end of year vacations delayed the start of the project
- BP-1 Milestone: Preliminary design (125 kW) with its performance variables compared with target metrics – Due end of Sept 2020 - **Completed Apr 2021**
- BP-1 Milestone: Detailed sectional stator with in-slot cooling – Due end of Dec 2020 – Go/No-Go Review – **Received no cost extension for phase-1 till Jun 2021 - Completed Apr 2021 – Received approval for phase-2 and contract extended.**
- BP-2 Milestone: Build, test and validate sectional stator to validate in-slot cooling as function of current density – Due Dec 2021 – **Extended to June 2022, significant delays associated with supply chain, shipping delays, prototype build.**

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Project Milestones & Status

Milestone #	Milestone	Type	Description	
1.1	Target performance metrics	Technical	UTRC in collaboration with John Deere shall develop a comprehensive target performance metric to be achieved during the duration of the proposed project by month-1	100% complete
2.1	Identify optimal operating speed and thermal management approach	Technical	UTRC team shall develop conceptual design of the motor and identify optimal operating speed (> 20,000 RPM) and suitable cooling mechanism by month-4	100% complete
3.1	Preliminary design meeting target performance specifications	Technical	Preliminary density of the in-slot cooled 125kW motor with its performance comparison against target power density of 50 kW/l and cost target of $6/kW by month-12	100% complete
4.1	Detailed design drawings for sectional stator	Technical& Go/No Go	Detailed design and drawings for a sectional prototype with in-slot cooling to validate slot fill factor and in-slot cooling performance by month-15. This is also a Go/No-Go decision point for the proposed project	100% complete
6.1	Experimental validation	Technical	Experimental results and validation of model prediction of optimal current density for a given maximum hot spot temperature by month 23	Phase-2 contract approved & signed. Prototype build: 80% No cost extension requested…
8.1	Reporting	Technical	Quarterly and final reporting as per DOE requirements.	

Specifications	SOA	Target Metrics	Current Design
Power Density (kW/L)	5.7	≥ 50	50.3
Cost ($/kW)	4.7	≤ 6	~6.3
Life (-)	1X	≥ 2X	1.95X
Peak Power (kW)	55	125	125
Max Speed (RPM)	2,800	≥ 20,000	20,000
DC Bus Voltage (V)	325	700	700
Volume (L)	25-35	≤ 2.5	2.4

Accomplishments Till Date

- Completed preliminary (multi-physics modeling &) design of proposed MACHINE concept
- Electric Machine Design
  - Completed preliminary design incorporating multi-physics constraints and design requirements
  - Completed loss modeling to provide inputs to thermal modeling
- Thermal Management
  - Completed preliminary design of in-slot cooling through channels incorporating ground insulation and effective stranded copper/insulation structure
  - Design refinement capturing final iteration
- Structural Design
  - Complete verification of electromagnetic forces on the stator and its impact on the structure
  - Complete rotor permanent magnet retainment design and safety factors

Summary / Current Work

- Complete multi-physics based preliminary design of proposed MACHINE concept
- Proposed design meets target power density (50.3 kW/l), life by 1.95X and cost $6.3/kW
- Proposed design meets power density and life requirements and narrowly missed cost targets due to limited information from supply chain on high volume production cost
- Complete design drawings for sectional stator (planning to build during phase-2)
- Current working with a local vendor to validate the designed fill factor and in-slot cooling structure

Current Work

- Build a section stator mimicking the preliminary design – 80% completed
- Validate the thermal management performance for a given heat loads
- Document findings and report to DOE/VTO through quarterly reports

*Any proposed future work is subject to change based on funding levels